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CURRENT FLOW AND EFFICIENCY OF GE P-N JUNCTIONS IN TRIPLE-JUNCTION GAINP/GA(IN)AS/GE SOLAR CELLS FOR SPACE APPLICATIONS.

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ABSTRACT: Photovoltaic converters based on n-GaInP/n-p Ge heterostructures grown by OMVPE at different conditions of p-n junction formation have been investigated. The heterostructures are intended for narrow bandgap subcells in triple-junction GaInP/GaInAs/Ge solar cells. It has been demonstrated that along with diffusion current component there is tunneling one in the Ge p-n junctions. Therefore, the two-diode electrical equivalent circuit of Ge p-n junction was used. The diode parameter values for both current components were determined by analyzing both dark and light I-V dependences. It has been shown that elimination of the tunneling current component allows increasing the Ge photovoltaic converter efficiency by ~1 % at non-concentrated solar radiation. Due to using the concentrated sunlight, the effect of tunneling current on the Ge based photovoltaic device efficiency can come to naught at the photogenerated current density of ~ 1.5 A/cm^2.

Keywords: multijunction solar cell, OMVPE, current flow.

1 INTRODUCTION

Since the introduction of spacecrafts with solar arrays based on homojunction GaAs solar cells (SC) into operation, and later, creation of AlGaAs/GaAs heterostructures [1,2], SCs based on $A^{III}B^{V}$ are successively used for power supply of artificial satellites.

As a results of the development of the OMVPE technology, monolithic multijunction solar cells (MJ SC) have been created, in which the “traditional” semiconductor Ge is used as a substrate and simultaneously as a narrow band subcell for the wideband dualjunction GaInP/GaAs SC [3-6]

In spite of the development of mechanically stacked MJ SCs [7] and present tendency to rise the number of p-n junctions [8], the monolithic triple-junction solar cells based on the GaInP/GaInAs/Ge structure are to-day the most competitive and effective solution for power supply of spacecrafts [9] and are finding ever increasing use in terrestrial photovoltaic installations.

Thus, it can be said that an interest has been inspired to the investigation of the Ge p-n junction first of all due to its use as the narrow-band subcell of a MJ SC.

Germanium is a suitable material for the substrate in the MOVPE of $A^{III}B^{V}$ semiconductor crystals. It is chemically compatible with Al-Ga-In-P and Ga-In-As compounds and ensures the absence of phase transformation with growing components. Ge has close values of the thermal expansion coefficient and lattice constant to those of the binary compound GaAs. From the space operation standpoint, the increased mechanical strength of Ge is an essential factor, which allows decreasing the thickness of the structures and SC weight and increasing the specific (per weight unity) power output in high-effective solar arrays. Besides, the germanium p-n junction included into the process of photo-conversion in a MJ SC allows extending its photosensitivity up to wavelength of 1800 nm.

Previously, the Ge p-n junctions were actively investigated with the aim to create rectifiers, transistors, photodiodes, etc. It has been established that the forward current flow mechanism is diffusion one (the ideality factor A is equal to 1) and results from recombination of electrons and holes thermo-injected into the quasineutral p- and n- regions of the p-n junction (Shokley diffusion component [10,11]). The saturation diffusion current value was about 10^{-6} A/cm^2 at RT [12]. The recombination component resulted from recombination of electrons and holes thermoinjected into the space charge region of the p-n junction was absent. However, the excess (by Esaki`s terminology [13]) component, which, at reverse bias, gave the saturation current density in the range of ($10^{-4} - 10^{-3}$) A/cm^2 [14 §12.2, 12]. But the excess current flow mechanism itself in non-degenerate Ge p-n junctions was not studied and discussed.

Nevertheless, as it is shown in the present work, the role of the excess component may be essential for SCs in the conditions of converting the low-intensive (the sunlight concentration ratio X<1), non-concentrated (X=1), and also slightly-concentrated (X<30) sunlight. The slightly-concentrated sunlight is realized in photovoltaic modules with linear lens concentrators [15].

The aim of this work was to study the n-GaInP/ n-p Ge photovoltaic heterostructure, which is intended for using as the “bottom subcell” of a triple-junction GaInP/GaInAs/Ge SC. This heterostructure consists of a germanium p-n junction and a wide-band n-GaInP window acting also as the phosphorus source for diffusion doping the p-Ge substrate with donors in forming the p-n junction.

For this purpose, test Ge photovoltaic converters (PVC) have been fabricated and the dark and load (under light) current-voltage characteristics (CVC) have been investigated. It has been shown that the dark CVCs should be approximated by the two-exponential model allowing for both diffusion and excess currents components. It has been established that the excess component has temperature dependences similar to those of the excess tunneling components in hetero p-n junctions [16] and Schottky barriers [17]. Approximations by the two-exponential model of the photovoltaic dependencies of the open current voltage (V_{oc}) and efficiency (η) on the photogenerated current J_g proportional to illumination has been curried out. The effect of the excess current on the sunlight conversion efficiency of the Ge PVC and, correspondently, of the

MJ SC has been odserved.

Thus, it has been shown that the tunneling current flow should be taken into account in photovoltaic Ge p-n junctions together with the diffusion one. The effect of the tunneling mechanism on the device efficiency is particularly essential in regimes of conversion of the slightly-concentrated, non-concentrated and low-intensive sunlight. The necessity to use a two-diode electrical equivalent circuit for describing the Ge p-n junction has been shown.

2 SUBJECT OF INVESTIGATION

For fabricating the n- GaInP/n-p Ge structures, the OMVPE technique was applied. The structures were being grown on the installation of laboratory type with a horizontal reactor at 100 mbar. The crystal growth was carried out on Ge-p(Ga) (100) substrates misoriented by 6^0 along the [111] direction 50 mm in diameter. The following metalorganic compounds were used as the third group element sources: trimethylgallium (TMGa), and trimethylindium (TMIn). Arsine (AsH3) and phosphine (PH3) were used as the fifth group element sources. Monosilane (SiH4) was used as a source for the n-type doping impurity.

The p-n junction in the Ge substrate was formed by diffusion of phosphorus (P) atoms from the growing nucleation GaInP layer (wide-band "window" for the Ge p-n junction). The heterostructures grown in such a way reproduce the narrow-band Ge subcell in the MJ SC. N^+-GaAs was grown as a contact layer for the following fabrication of test Ge PVCs. Formation of the Ge PVC contact structures was done by photolithography. The contact structure configuration was being elaborated for SCs intended for application in photovoltaic modules with linear lens concentrators [15]. On the PVC face surface, the double-layer ZnS/MgF_2 antireflection coating was deposited.

At different conditions of the nucleation GaInP layer growth, two groups of structures were grown: 1 – with alike thickness of the GaInP wide-ban window, but with different phosphorus atoms gas diffusion time; 2 – with alike gas diffusion, but different thickness of the GaInP layer (different solid phosphorus atoms diffusion time). The wide-band window thickness was being varied within 35-300 nm. The gas diffusion (annealing) time at high partial phosphine pressure was 5-40 min. The formation conditions and parameters of the heterostructures are accumulated in Table 1.

Ge PVC	Anneal. in PH_3, min	GaInP "window", nm	J_g, (AM0, X=1, Q_{ext}), mA/cm^2	J_g, (AM0, X=1, Q_{int}), mA/cm^2	J_{od} (E_d= 0.025), A/cm^2×10^{-6}	J_{ot} (E_t= 0.169), A/cm^2×10^{-3}	R_s, Om cm^2
# 1	-	35	52,07	57,68	5.2	1,4	0.014
# 2	-	100	51,06	56,77	2,9	1,1	0.013
# 3	10	100	50,57	55,29	2,4	3,3	0.013
# 4	40	100	49,83	55,42	4,4	0,5	0.010
# 5	-	300	50,00	53,25	6,8	1,0	0.014

Table I: Formation condition and parameters of the n- GaInP/n-p Ge heterostructures and Ge PVC parameters at absolute temperature 300 K.

In particular, Table 1 shows that values of the external quantum yield (Q_{int}) differ only in the absorption region of GaInP (for Ge PVC with different thickness of window). It has been shown in [18, 19] that the preepitaxial conditions (for example, annealing in phosphine) determine the reconstruction of the Ge substrate surface and, hence, the quality of growth on Ge. The fact that photogenerated current doesn't depend on preepitaxial conditions allows making the following conclusions on formation of Ge p-n junctions during OMVPE. First, there is a possibility to vary preepitaxial conditions in the wide range depending only on the requirements for forming favorable reconstruction of the Ge surface. Second, there is a possibility to vary "window" thickness dictated by the requirements to the divice parameters.

3 ANALYSES OF EXPEREMENTAL RESULTES

3.1 Dark I-V curves of the Ge p-n junctions.

As is known, the basic photovoltaic characteristics of a p-n junction (for example, dependencies of V_{oc} and efficiency on the photogenerated current, J_g) are produced from the dark IVC and, for this reason, are presented by the same parameters.

Fig. 1 presents the dark forward and reverse IVCs of a Ge PVC #4 (Table 1) recorded for the temperature range of 90-330 K.

Approximation of the forward branch of the IVC by the sum of the components of exponential form (1a) has show that, in the operation temperature range of 120-330 K, the forward current consists of the "classical" diffusion component and the excess one, which, as will be shown later, has the tunneling character:

$$J = J_{od} \cdot \left[\exp\left(\frac{V - J \cdot R_s}{E_d} \right) - 1 \right] + J_{ot} \cdot \left[\exp\left(\frac{V - J \cdot R_s}{E_t} \right) - 1 \right],$$

(1a)

where J is the current density in the external circuit, V is the voltage, R_s is series resistance of the device, J_{od} is the saturation current of the diffusion component (preexponent), J_{ot} is the preexponent ("saturation" current) of excess (tunneling) component, E_t is the characteristic potential of the tunneling component, E_d is the characteristic (thermal) potential of the diffusion component, which may be expressed through the ideality factor $A_d = 1$:

$$E_d = \frac{kT}{q} \cdot A_d = \frac{kT}{q} \quad , \qquad (1b)$$

where q – the electron charge, k – the Boltzmann constant, T – the absolute temperature.

Thus, the “traditional” practical single-diode equivalent circuit [20 §3.9] for the Ge p-n junction should be replaced by dual-diode one.

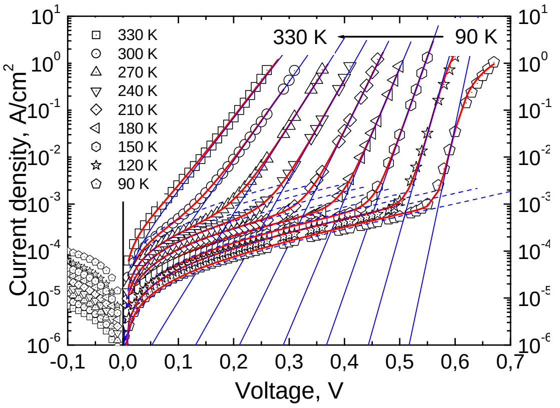

Figure 1: Forward and reverse dark current-voltage characteristics of the Ge p-n junction at different temperatures (from 90 to 330 K). Symbols are the experimental data, (——) − the calculations by the two-exponential model, (——) − the diffusion components (A_d=1), (— —) − the tunneling components (E_t=0,015V).

At 300 K, the saturation current $J_{od} \approx 10^{-6}$ A/cm^2, which agrees well with Shockley’s data [12] for the Ge p-n junctions and correspond to the diffusion mechanism of current flow. The reverse current values extrapolated to zero voltage (Fig.1) coincide with the excess forward current preexponential factor J_{od} and by its order of magnitude is close to the reverse currents observed before [12, 14 §12.2].

The values of the preexponents (J_{od}, J_{ot}) and characteristic potentials (E_d, E_t) for all investigated Ge PVCs at 300 K are tabulated (Table 1).

In the low temperature region (≤ 120^{0}K), the IVC shape is, apparently, affected by the series (probably nonlinear) resistance, which rises strongly (by an order of magnitude) in decreasing temperature.

It is seen from Table 1 that the presence of both the diffusion and excess currents is the general property of all investigated p-n junctions, and that the characteristic parameters (J_o , E) for both current flow mechanisms in different Ge PVCs have close values. This says about the presence of the diffusion and excess currents as a typical situation for the Ge p-n junctions.

Fig.2 presents temperature dependencies of the J_o and E parameters obtained at approximation of the IVC by formula (1a). For theoretical substantiation of the nature of two current flow mechanisms in the Ge p-n junctions, the experimental temperature dependences of J_{od}, J_{ot} are compared with rated ones.

The expression for the diffusion saturation current J_{od} may be written in a form accounting for the temperature dependence of the band-gap:

$$J_{od} = q \cdot N_c \cdot N_v \cdot \left(\frac{D_{pN}}{n_N \cdot L_{pN}} + \frac{D_{nP}}{p_P \cdot L_{nP}} \right) \cdot e^{-\frac{Eg}{k \cdot T}} \quad , \qquad (2)$$

where N_c and N_v are the effective densities of states in the conduction and valence bands, D_{nP} , D_{pN} and L_{nP} , L_{pN} are the diffusion coefficients and diffusion length, respectively, in N - and P - regions, , n_N and p_P are the majority charge carriers concentrations in N-emitter and P-base, E_g is the band-gap width.

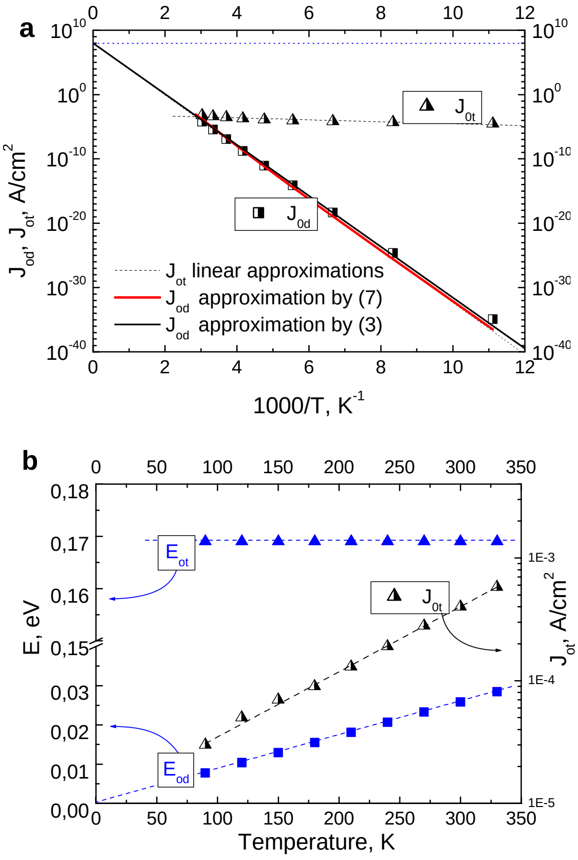

Figure 2: Dependencies of the diode parameters on the value of reverse (**a**) and forward (**b**) absolute temperature for the diffusion and tunneling components.

The temperature dependencies of germanium E_g in the range of 120-330 K are described by the well known empirical formula [14 §10.1, 20 §2.17]

$$E_g = E_{g0} - \beta \cdot T \quad , \qquad (3)$$

where the empirical constants E_{g0} = 0.785 eV, and β ≈ 4,0×10^{-4} eV/K.

In this case formula (2) may be written as:

$$J_{od} = J_o^{\infty} \cdot e^{\frac{-E_a}{k}\left(\frac{1}{T}\right)} \quad , \qquad (4)$$

where the to exponent temperature function activation energy $E_a = E_{g0}$, and J_o^{∞} is a weak compared. Approximation of the experimental J_{od} data by formula (4) at a fixed E_a value (Fig. 2a − black solid line) allows obtaining an extrapolated to $T \to \infty$ experimental value $J_o^{\infty} \approx 1\times10^8$ A/см2.

The rated value of J_o^{∞} at $T \to \infty$ in the exponent of formula (4) is determined by the expression:

$$J_o^{\infty} = q \cdot N_c \cdot N_v \cdot \left(\frac{D_{pN}}{n_N \cdot L_{pN}} + \frac{D_{nP}}{p_P \cdot L_{nP}} \right) \cdot e^{\frac{\beta}{k}} \qquad (5)$$

In this case, estimation of the diffusion coefficient values is taken from the tabular data for mobilities of electrons and holes in Ge [20 ,21] and they are: $D_{nP} \le$ 100 cm^2/s, $D_{pN} \le 50$ cm^2/s. The diffusion length value were determined previously in [22] in analyzing the Ge PVC spectral characteristics, and they are: $L_{nP} = 50$ μm, $L_{pN} = 0.35$ μm. N_c and N_v values for Ge, which also depend on temperature, were calculated with the help of the expressions [14 §10.1]:

$$N_c = 2\times10^{15} \cdot T^{\frac{3}{2}} \ , \quad N_v = 1.17\times10^{15} \cdot T^{\frac{3}{2}} \qquad (6)$$

at temperature values, for which the empirical expression (3) is used.

As a result, the rated value of J_o^{∞} is from 8.7×10^7 A/cm^2 (for $T = 300$ K) to 1.4×10^8 A/cm^2 (for $T = 350$ K), what agrees well with the experimental values.

Thus, the experimental values of the saturation current obtained at different temperatures (90-330 K) correspond to the diffusion current flow in the Ge p-n junction.

Such a result is obtained by the use of the more appropriate (linear-quadratic) dependence of E_g on temperature according to the Varshni formula [23]:

$$E_g = 0.742 - \frac{4.8\times10^{-4} \cdot T^2}{T + 235} \qquad (7)$$

The rated dependence obtained by the formula (2) with the help of (7) approximates well the experimental value of the preexponent J_{od} within the whole investigated temperature range (Fig.2a – red solid line).

The characteristic potential E_d (Fig. 2b) is proportional to temperature with the ideality factor A_d = 1 (1b), which also confirms the diffusion nature of the current component.

The characteristic potential E_t for the excess current component does not, practically, depend on temperature within its whole range (Fig. 2b). Besides, the J_{ot} value depends weakly on T compared with the diffusion saturation current (Fig. 3 a,b). All this allows supposing that the excess current flow has the tunneling nature. Note that the tunneling mechanism model compared with the diffusion one was not thoroughly elaborated. It is associated, first of all, with that the nature of the tunneling mechanism is quite complicate and includes a complex of charge carrier transport phenomena. In spite of this, estimation of the temperature coefficient J_{ot} was carried out.

According to the models of tunneling mechanism [16, 24], the temperature dependence of the J_{ot} should be determined by the dependence of E_g on temperature and, for this reason, slightly increase with its rise. Analysis of the experimental data has shown the insignificant increase in J_{ot} with temperature, which is described by the linear dependence (Fig.2).

If one anticipates that only charge curriers on the edges of the allowed bands are participating in the tunneling process though the p-n junction (i.e. thermal “tossing up” of the charge carriers in the bands is neglected), the tunneling current value is written in the following form [16]:

$$J_t = J_{ot} \cdot e^{\frac{V}{E_t}} = J_{oot} \cdot e^{\frac{V - V_k}{E_t}} \ , \qquad (8)$$

where V_k is the contact potential difference between the quasineutral P and N regions.For a non-degenerated semiconductor, the $q \cdot V_k$ value is determined as the algebraic sum of the semiconductor band-gap and chemical potentials for electrons and holes in the quasineutral regions:

$$q \cdot V_k = E_g - k \cdot T \cdot \ln\left(\frac{N_c}{n_N} \right) - k \cdot T \cdot \ln\left(\frac{N_v}{p_P} \right) \qquad (9)$$

Substituting (9) in (8) with accounting for (3) and (6), we can obtain an expression for the temperature coefficient:

$$b = \frac{\Delta \ln J_{ot}}{\Delta T} = \frac{1}{q \cdot E_t} \cdot \left[\beta + k \cdot \ln\left(\frac{N_c \cdot N_v}{n_N \cdot p_P} \right) \right] \qquad (10)$$

The temperature coefficient b calculated by (10) is equal to 3×10^{-3} K^{-1} and coincides by an order of magnitude with the value determined from the experiment (Fig. 2b) - 9.2×10^{-3} K^{-1}. The threefold excess of the rated value above the experimental one is explained by that, in the (8), the thermo-tunneling character of the current flow, which was analyzed before only for the Schottky barriers [17], was not taken into account.

The temperature coefficient value for the J_{ot} and also independence of the characteristic potential E_t on temperature (Fig. 2b) indicate the tunneling nature of the forward current excess component.

Thus, the analysis of the dark IVCs and the theoretical estimations for the Ge p-n junctions grown in different conditions have allowed establishing the presence of both diffusion and tunneling components of the dark current and also determining their parameters.

3.2 Photovoltaic characteristics of a Ge PVC.

A set of IVCs (Fig.3) recorded at different sunlight concentration ratios has been analyzed, and their approximation (solid lines) was carried out by means of the proposed two-exponential model (1a,b) with selection parameters presented in Table 1. In the range of the considered sunlight concentration ratios (X<30), R_s has no effect on the IVC shape. All load IVCs are normalized to the short circuit current (J_{sc}), which is, practically, equal to the photogenerated one ($J_{sc} \approx J_g$) at this conditions.

For the load IVC, characteristic voltages are usually separated out, which are convenient for describing its shape (Fig. 3, insert), V_{oc}, V_m, V_η. Where V_{oc} is a voltage corresponding to the break of the external circuit; V_m is a voltage in the point (m) of the optimal load, in which its product by the current J_m gives the maximum power (P_m) generated on the load; V_η is the "efficiency" voltage determined by the equality:

$$P_m = V_m \cdot J_m = V_\eta \cdot J_g \qquad (11)$$

Since the photogenerated current density is proportional to the incident radiation power density, one may introduce an auxiliary value U_{conv}, which is alike for all load IVCs:

$$U_{conv} = \frac{P_{inc}}{J_g} \qquad (12)$$

Thus, the "efficiency" voltage is proportional to the efficiency with U_{conv} coefficient:

$$\eta = \frac{P_m}{P_{inc}} = \frac{1}{U_{conv}} \cdot V_\eta \qquad (13)$$

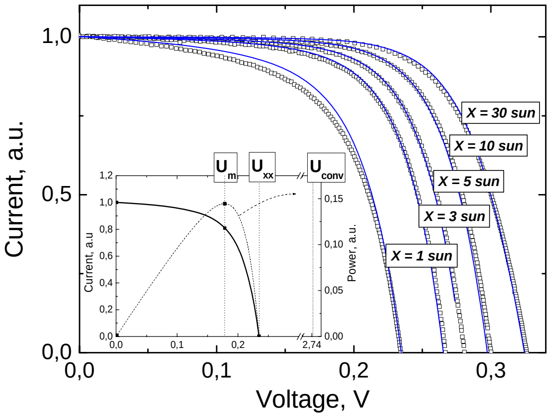

Figure 3: Load IVCs at different sunlight concentrations (X): (□) – experimental data, (——) – rated curves. The curves are normalized to corresponding short circuit current values. Insert shows the relative position of the characteristic voltages: V_m, V_{oc}, V_η and also U_{conv} value.

The dependencies of V_{oc}, V_m and V_η on the photogenerated current J_g (Fig. 4) were approximated on the base of the two-exponential model of the dark current (1 a,b). They consist of two components – diffusion and tunneling ones, which are described by the same set of the diode parameters as the dark IVC (table 1). In other words, the approximation parameters (J_0, E) can be found from analysis of only photovoltaic dependencies.

The $V_{oc}(J_g)$ dependence repeats the shape of the resistanceless dark IVC and can be approximated with the help of the expression (1a), where $R_s \to 0$ (therewith $J \to J_g$, $V \to V_{oc}$). For this reason, it is the most convenient for determining the parameters of the current flow diffusion mechanism. The value obtained in such a way for J_{od} and E_d coincided well with the values obtained from the analysis of the dark IVC at 300 K.

For determining the tunneling current parameters, the dependencies $V_m(J_g)$ and, especially, $V_\eta(J_g)$ are the most convenient, since, at any value of the photogenerated current, the contribution of the tunneling component to the "efficiency" voltage value is the greatest compared with other characteristic voltage (Fig. 4). Thus, the tunneling current preexponent value was specified by means of the numerical approximation of $V_\eta(J_g)$, $V_m(J_g)$ dependencies by the formulae obtained in [25], but taking into account the two-exponential model:

$$J_g = \sum_{i=d,t} J_{oi} \cdot \left(1+\xi_i(V_\eta + J_g \cdot R_s)\right) \cdot \exp\left(\xi_i(V_\eta + J_g \cdot R_s)\right), \qquad (14a)$$

where

$$\xi_i(V_\eta + J_g \cdot R_s) = \frac{V_{\eta o} + \sqrt{V_{\eta o} \cdot \left(V_{\eta o} + 4 \cdot E_i\right)}}{2 \cdot E_i}, \qquad (14b)$$

$$V_{\eta o} = V_\eta + J_g \cdot R_S \qquad (14c)$$

and

$$J_g = \sum_{i=d,t} J_{oi} \cdot \left(1 + \frac{V_{mo}}{E_i}\right) \cdot \exp\left(\frac{V_{mo}}{E_i}\right), \qquad (15a)$$

where

$$V_{mo} = V_m + J_g \cdot R_S \qquad (15b)$$

The series resistance R_s affects the shape of the $V_\eta(J_g)$ and $V_m(J_g)$ dependencies decreasing the values of the values of the characteristic voltages with photogenerated current and resulting in appearance of the maximum. The rated values of R_s are presented in Table 1.

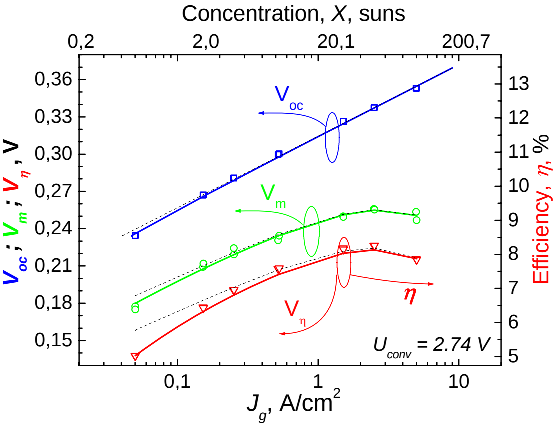

Figure 4: Dependencies of V_{oc}, V_m and $V_\eta \propto \eta$ on the photogenerated current density J_g: experimental data (color symbols), approximation by the two-exponential model (color solid lines) and approximation by the "traditional" one-exponential diffusion model (dark dashed lines).

It is seen that the rise of the tunneling current decreases noticeably the V_{oc}, V_m and, especially, V_η at $X \leq 1$ and affects the sunlight conversion efficiency up to

$X \approx 30$. Removal of the current tunneling component ensures the increase in the Ge PVC efficiency by the value of up to 1% in converting the non-concentrated sunlight with the AM0 spectrum (Fig. 4).

3.3 The Ge subcell of a multijunction solar cell.

The test Ge PVCs considered above have the heterostructure similar to the narrow-band subcell of a MJ SC. This allows estimating the contribution of the Ge subcell to the photovoltaic characteristics of a MJ SC.

The following peculiarities should be taken into account therewith. The investigated Ge PVCs have (Table 1) high values of the photogenerated current ($J_g = J_{sc} =$ 49,8÷52,1 мА/см^2, X=1, AM0). The resulting J_{sc} in a MJ SC is limited by the minimal current from those generated by each subcell, and the resulting voltage is a sum of subcell voltages.

For the wide-band GaInP/Ga(In)As tandem, the photogenerated current value will be the greatest one, when the J_{sc} values of the top GaInP and middle GaInAs subcells will be matched and maximal [26]. Thus, the contribution of the Ge subcell in the MJ SC efficiency is limited by the resulting current of the top wide-band tandem and is determined by the values of V_{oc} and the IVC fill factor (FF).

Nevertheless, the excess of the Ge subcell photogenerated current over J_{sc} of the wide-band tandem is important, because the effect of the FF value in the Ge subcell on the shape of the MJ SC IVC is minimal.

In a MJ SC, the Ge subcell photogenerated current value is lower than J_{sc} (Table 1) for test Ge PVCs. Actually, the wide-band GaInP/GaInAs tandem is an optical filter for the Ge subcell limiting the range of its spectral photoresponse in the short-wavelength region due to absorbing the radiation with wavelength < 890 nm in the GaInAs layers.

Taking into consideration the pecularities mentioned above, a procedure for estimating the contribution of the Ge subcell in the MJ SC efficiency has been proposed.

The MJ SCs were fabricated on the base of the monolithic triple-junction GaInP/GaInAs/Ge structure grown by the OMVPE technique and had the contact design similar to that of the test Ge PVCs. The MJ SC efficiency was 26% in converting the direct (X=1) sunlight and 28,2% in converting the concentrated (X=20) sunlight (AM0).

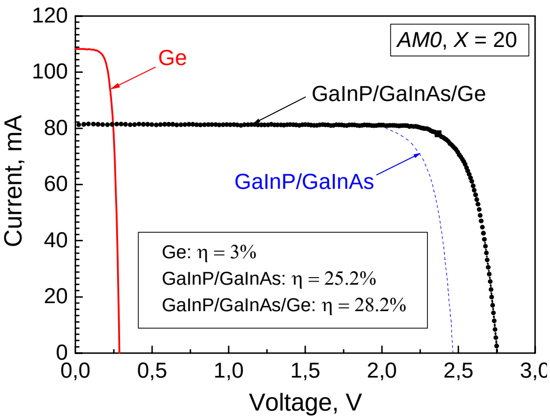

Figure 5: Load IVCs: calculation by the two-exponential model for a Ge subcell, experemental IVC for a triple-junction GaInP/GaInAs/Ge SC and IVC simulated for dual-junction GaInP/GaInAs SC.

The photogenerated current calculated for the GaInP/GaInAs optical filter was additionally corrected with allowing for the difference between properties of the antireflection coating of the Ge PVC and the MJ SC. The J_{sc} value obtained from the calculation was ~ 30 A/cm^2, which exceeds noticeably over the wide-band tandem J_{sc}.

Fig. 5 shows the rated load IVC of the Ge subcell and recorded IVC of two MJ SCs at X=20. Subtraction of voltage on the first curve from those on the second curve (Fig. 6) allows at fixed current values forming the load characteristic of the wide-band GaInP/GaInAs tandem and calculated both its and Ge subcell contributions in the MJ SC efficiency. The Ge subcell efficiency contained in the triple-junction GaInP/GaInAs/Ge SC was ~2.3% (AM0, X=1). The Ge subcell contribution in the MJ SC efficiency rises with the sinlight concentration ratio reaching ~3,4% at $X = 20$.

4 CONCLUSIONS

Photovoltaic n-GaInP/n-p Ge heterostructures intended for using as the narrow-band subcells of the triple-junction GaInP/GaInAs/Ge solar cells for space application have been investigated.

It has been shown that the maximum contribution of the Ge subcell efficiency to that of the sunlight conversion by a MJ SC (with η=28,2%, X=20, AM0) may reach ~3.4%.

It has been shown for the first time (from the temperature dependence of the dark IVCs, 77-330K) that the excess current flowing (together with the diffusion one) in the Ge photovoltaic p-n junctions has the tunneling character. As a result, for approximating current-voltage (dark and light) characteristics and photovoltaic dependencies (V_{oc} , V_m and V_η ($\propto \eta$) on J_g ($\propto X$)), it is necessary to use the two-exponential model allowing for both diffusion and tunneling current flow and the two-diode electrical equivalent circuit corresponding to it. The values of the diode parameters for both current flow mechanisms (J_{od}, E_d, J_{ot}, E_t) have been determined. Also, a possibility to determine all diode parameters has been shown from both dark IVCs and the only photovoltaic dependencies.

The effect of the tunneling current on the Ge subcell efficiency has been estimated. It is particularly essential, at the low-intensive and non-concentrated ($X \leq 1$) sunlight. Due to this, the decrease in the Ge subcell efficiency in converting the direct ($X = 1$) space sunlight is ~1%. The effect of the tunneling current practically come to naught in increasing the concentration ratio up to $X \approx 30$ ($J_g \approx 1{,}5$ A/см^2).

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